



Tribological behavior of Al–6.5%, –12%, –18.5% Si alloys during machining using CVD diamond and DLC coated tools



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ABSTRACT

Tribological behavior of cast Al–Si alloys was studied by considering samples from hypo-eutectic (Al–6.5% Si), eutectic (Al–12% Si) and hyper-eutectic (Al–18.5% Si) compositions that were subjected to dry drilling experiments. Tool materials tested consisted of hydrogenated diamond-like carbon (H-DLC), CVD diamond coated and uncoated WC–Co drills. Tool failure mechanisms were identified and correlated with the drilling torques. The drilling torque vs. number of holes curves typically exhibited three stages, each identified with a characteristic slope (m). A failure criterion was established, such that when $m \geq 1.0 \times 10^{-2}$ N m the onset of tool failure in dry drilling of Al–Si alloys could be predicted. For hypo-eutectic and eutectic Al–Si alloys drilled using uncoated WC–Co the failure criterion was satisfied rapidly (<70 holes) and extensive aluminum adhesion to the drill occurred. The use of H-DLC and CVD diamond coated drills reduced aluminum adhesion and built-up edge formation, and maintained $m \leq 1.0 \times 10^{-2}$ N m throughout the drilling tests range. Drilling of hyper-eutectic Al–Si alloys with the H-DLC coated drills led to shortened tool lives characterized by flank wear as the primary Si particles abraded the coating and increased the friction. CVD diamond coated drills produced low tool wear and maintained low steady state m values. It was concluded that during dry drilling of Al–Si alloys, where aluminum adhesion was a performance limiting factor, H-DLC coatings could replace CVD diamond tools.

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1. Introduction

Al–Si alloys castings, both hypo- and hyper-eutectic grades, are widely used in automotive and aerospace industries. These alloys are difficult to machine regardless of their Si content but for different reasons. During machining of low Si content alloys, aluminum adhesion to the tool materials such as HSS and WC–Co is the main problem—especially during dry drilling and tapping whereas machining of high Si content alloys often causes flank wear of the tool. Thus, during Al–Si alloy machining, both aluminum adhesion and tool wear may cause premature tool failure depending on Si content [1–3]. Past studies have shown that conventional wear resistant tool coatings that are effective for machining of ferrous materials are not nearly as efficient when used on hypo-eutectic Al–Si alloys as they fail to prevent aluminum adhesion. Metal nitrides based hard coatings, including TiN, TiCN, and TiAlN, are among those that have demonstrated unsatisfactory tribological performance (high friction and adhesion) against these alloys under dry sliding contact [4]. Research work aimed at improving machining performance of the pro-eutectic and near eutectic Al–Si alloys should therefore consider adhesion mitigating properties of the tool coatings as the primary selection criterion. It was shown that diamond

and diamond-like carbon (DLC) coatings significantly diminish the adhesive transfer of aluminum to the tools during dry drilling and tapping operations [5–9]. Yet the frictional behavior of the DLC coatings, both hydrogenated (H-DLC) with about 40 at.% H and non-hydrogenated grades (NH-DLC) with less than 2 at.% H has certain limitations, primarily because their properties are sensitive to changes in atmospheric humidity and temperature. The coefficient of friction (COF) of H-DLC increases abruptly at above 200 °C and that of NH-DLC above 100 °C [10–12]. Polycrystalline diamond (PCD) is often the preferred tool material [13–15] for machining applications where high temperatures are generated. The diamond tool coatings deposited by cathodic vapor deposition (CVD) method combine high hardness with wear resistance and possess satisfactory adhesion mitigating properties and thus are considered to be the state of the art tool material for Al–Si machining [16,17].

Dry machining of metals is desirable due to its environmental benefits but is yet to be applied to large scale manufacturing. Dry machining generates the most demanding machining conditions. However, for laboratory scale studies undertaken for the purpose of delineating performance limitations of the tool coatings. Dry machining tests may provide useful baseline information for potentially robust and cost effective coatings for Al–Si machining processes. A review of the existing literature on the dry machining of Al–Si alloys using DLC coatings, PCD and CVD diamond coated tools is provided in Sections 1.1 and 1.2.

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1.1. Dry machining of Al–Si alloys using PCD and CVD diamond coated tools

Heath [13] compared cutting performance of PCD tools with the uncoated WC–Co in cutting of hypereutectic Al–20% Si alloy. An increase in tool life by 500 min was observed for the PCD tools while the uncoated WC–Co tool lasted for 50 min. Oles et al. [14] tested CVD diamond and PCD tools in turning of Al–18% Si with both materials showing similar tool lives. However, the surface roughness produced by the CVD diamond tools ($0.84\text{ }\mu\text{m}$) was slightly higher than that generated by the PCD tools, ($0.62\text{ }\mu\text{m}$). Shen [15] compared the machining performance of CVD diamond coated inserts to the uncoated WC–Co inserts in turning of Al–18.5% Si. While the uncoated WC–Co tools failed after 7 min the tool life was extended to 70 min with the use of CVD diamond coated tools which also required two times lower cutting force (0.8 kN) compared with the uncoated WC–Co. Liang et al. [16] by conducting turning experiments on Al–18.5% Si observed that smoother surfaces with an average roughness, R_a , of $0.6\text{ }\mu\text{m}$ were obtained for the PCD inserts compared to R_a of $0.85\text{ }\mu\text{m}$ generated by the uncoated WC–Co, which was attributed to the higher wear of the WC–Co tool inserts. Gomez et al. [17] reported that during turning of Al–18.5% Si the use of CVD diamond coatings with a CrN/Cr interlayer prolonged the tool life by 50%. Ng et al. [18] studied face milling of a hypo-eutectic alloy Al–6.5% Si and noted a high cutting force of 900 N for the uncoated WC–Co tool and significant flank wear that also produced a high surface roughness. A 25% reduction in the cutting force was achieved with the use of a PCD tool. Roy et al. [19] studied the turning of a eutectic Al–12% Si alloy where a twofold reduction in the cutting force was observed for the CVD diamond coated tools compared to the uncoated WC–Co tools (70 N) whose surfaces exhibited extensive aluminum adhesion.

In summary, both PCD and CVD diamond coatings were observed to reduce flank wear during machining of the hyper-eutectic Al–Si alloys. For the eutectic and hypo-eutectic Al–Si alloys, these coatings also showed better performance than the uncoated tools by reducing Al adhesion. However, manufacturing and finishing costs of the PCD tool inserts and CVD diamond coating are high, although they are being used for machining of critical automotive components made of Al–Si such as the engine block and valve bodies. DLC coatings have also shown low friction and good Al adhesion mitigating properties in tribological experiments [8–12]. It is due to this reason and because of their low cost DLC coated tools have the potential to be used in machining Al–Si castings. Previous studies that considered the cutting performances of DLC coatings in aluminum machining are reviewed in Section 1.2.

1.2. Dry machining of Al–Si alloys using DLC coated tools

DLC (with 10–20 at.% H) coated tools reduced the thrust force to 40 N compared to uncoated WC–Co (50 N) in the turning experiments conducted on Al–16% Si by dos Santos et al. [20]. Dasch et al. [21] tested different carbon based coatings and compared them with PCD during drilling of Al–6.5% Si. NH-DLC coating that generated power consumption as high as 8 HP did not provide much improvement over the HSS

drills (10 HP). However, using a blend coated (NH-DLC/H-DLC) drill a low 4 HP of power consumption was recorded and resulted in a better performance than the H-DLC coated tools. A correlation was found between the amount of aluminum adhesion and the high power required to drill a hole as high aluminum adhesion resulted in chip clogging. Wain et al. [22] tested the H-DLC coated drills during the drilling of Al–6.5% Si and reported that a prolonged tool life (≥ 400 holes) was observed when using this coating compared to the uncoated HSS (40 holes). The improvement in tool life was consistent with the small built-up edge (BUE) formed when drilling with the H-DLC coated drill [21]. Bhowmick and Alpas [23] measured the torques and thrust forces generated when H- and NH-DLC coated HSS drills were used in drilling of Al–6.5% Si. H-DLC coated drill produced consistently lower average torque (2.11 N m) compared to NH-DLC coated (2.63 N m) and uncoated (4.11 N m) HSS drills and produced smaller torque spikes (occasional peaks on the torque-time plots) that are indicative of low aluminum adhesion to the coating surface. The metallographic observations confirmed that H-DLC coated drills almost entirely eliminated metal transfer to the drill flutes and diminished BUE formation on the drill's flank face and cutting edge. The tapping of Al–6.5% Si was studied by Bhowmick et al. [24] using H-DLC coated taps that were shown to produce lower average torque (1.01 N m) and a smaller amount of Al transfer to the taps compared to tapping using uncoated HSS tools (3.18 N m).

In summary, DLC coatings were found to improve tool lives of HSS drills and the H-DLC coatings provided slight advantage over NH-DLC coatings in reducing the cutting forces during dry cutting of aluminum alloys. Studies on DLC coated tools, however, are limited to Al–Si alloys with low Si concentrations ($< 12\%$ Si). Meanwhile it becomes clear from the survey in Section 1.1 that the coatings' performances may vary with the Si content and also the tool life limiting damage mechanisms change depending on whether DLC, PCD and CVD diamond coatings were used, as summarized in Table 1. This work evaluates the tribological performance of H-DLC coated tools in drilling of Al–Si alloys with low and high Si percentages in comparison with CVD diamond using a common experimental methodology. The experimental methodology incorporates the following stages: (i) measurement of the drilling torques until tool failure or to a predetermined number of drilling cycles; (ii) determination of drilling induced temperature and examination of its role on tool life; (iii) delineation of the role of the coefficient of friction COF on the drilling torque and temperature; and (iv) characterization of aluminum transfer to the tool contact surface and flank wear using metallographic techniques, which are then used to rationalize the tool failure mechanisms.

2. Experimental details

2.1. Properties and microstructures of Al–Si alloys

The Al–Si alloys studied consisted of two sand cast alloys, one with $6.5\text{ wt.\% Si}$ (319 Al) and the other with $12.0\text{ wt.\% Si}$, and a die cast

Table 1

Summary of previous studies on Al–Si alloys describing machining processes, tool coatings, cutting torques, forces, tool lives and tool failure mechanisms.

Materials	Machining processes	Tools/coatings	Cutting force/torque	Tool life (min)	Failure mechanism	References
Al–20% Si	Cutting	PCD	–	500	Flank wear	[13]
Al–18% Si	Turning	PCD	–	10.2	Flank wear	[14]
Al–18% Si	Turning	CVD diamond	800 N	70	Flank wear	[15]
Al–18% Si	Turning	PCD	–	–	Flank wear	[16]
Al–18% Si	Turning	CVD diamond	–	> 5	Flank wear	[17]
Al–12% Si	Turning	CVD diamond	70 N	–	Adhesion	[18]
Al–6.5% Si	Milling	PVD	225 N	–	Adhesion	[19]
Al–16% Si	Turning	H-DLC	40 N	–	Flank wear	[20]
Al–6.5% Si	Drilling	H-DLC	7 N m	> 8.25	Adhesion	[21]
Al–6.5% Si	Drilling	H-DLC	6.51 N m	> 7.50	Adhesion	[23]
Al–6.5% Si	Tapping	H-DLC	1.01 N m	> 10	Adhesion	[24]

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